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Development of Hybrid Vehicle for ground service handling operations

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Abstract

The objective of this work is to develop a hybrid power pack which both improves fuel efficiency and reduces the emission of ultra-fine particles at the same time. The power pack consists of a fuel cell and a battery and it operates on methanol-water mixture. The power pack represents a cost effective solution, while the hybrid vehicle has a number of advantages compared to an internal combustion engine (ICE) diesel powered vehicles: no particle emissions; possible indoor usage in hangars; fuel efficiency and fossil free transportation. Particle emissions from diesel ICE utility vehicles at the airport handling area (luggage, passenger in/out, fueling and service) represent serious health hazards. Especially the emission of ultra-fine particles represents a significant problem for the working environment at airports. The advantage of this concept is that the size of the individual components can be reduced (as compared to a non-hybrid system), while improving the overall energy efficiency by using the most efficient hybridization for a given power requirement (5 kW). The fuel cell technology is based on High Temperature PEM fuel cells (HTPEMFCs) from Danish Power Systems Company. The battery pack, battery management system (BMS) and on-board charger are being developed by Lithium Balance Company.

Keywords: Hybrid vehicle; PEM Fuel Cell; MeOH reformer; hybrid power pack, biofuel.

1. Introduction

The target of the present project is to provide a full-working hybrid-electric vehicle integrated with a 5-kW fuel cell system. The main source of power in the car is given by electric batteries, while the fuel cell (FC) system is supposed to serve only as a battery lifetime extender. According to the simulations performed by Andreasen *et al*. [1], an average increment in vehicle autonomy of more than 45% for a standardized driving cycle is possible (the increment in battery life clearly depends on the ratio between the motor size and the FC power capacity. In this project, a FIAT Scudo van with a 50-kW electric motor is provided by the project partner Lithium Balance A/S [2], while the 5-kW FC stack is provided by the company Danish Power Systems [3] in cooperation with Serenergy Company [4]. The FC system is supposed to operate only in one single working point with an on/off regulation. The fuel cell stack is a high-temperature proton exchange membrane (HTPEM) and its operative temperature ranges between 120 and 190 °C. In this project, the operative temperature is set to 160 °C. The working point of a fuel cell is set to 0.6 V and 0.4 A/cm^2. Thereby, 120 cells in series would produce 5 kW at 72 V with a current of 69.4 A. It was decided to feed air and hydrogen with a stoichiometry of 1.5 for H_2 and 2.5 for O_2, leading to a molar oxygen-to-fuel ratio of 1.67. At these working conditions, the fuel cell is supposed to have efficiency of about 50%. A HTPEMFC requires hydrogen as fuel, but has a higher tolerance to CO content compared to traditional PEM fuel cells [5]. This allows the fuel cell to be fed with a hydrogen-rich mixture coming from a reforming process. In this project, a methanol and water mixture is fed to an on-board reformer to provide a 70-75% hydrogen-rich mixture for the fuel cell. The inlet reformate fuel comes in the FC with a temperature between 160 and 250 °C, while the air does not need to be preheated. The temperature and heat generation of the fuel cell is controlled by the coolant loop where it was decided to employ triethylene glycol as coolant. Figure 1 provides a conceptual scheme of the working fuel cell. In the methanol plant layout, a liquid mixture of 40% methanol and 60% H_2O (molar base) is fed to an evaporator, when it is heated up to about 250 °C; after the evaporator, the methanol-steam gas mixtures crosses a reformer, where a heat supply ensures a proper fuel conversion. In the end, a hydrogen-rich mixture leaves the chemical reactor at 280 °C.

2. Waste heat recovery

A consistent waste heat recovery is present in this system: the off-gas coming from the fuel cell is mixed with external air and burnt in a catalytic burner. The combusted gases, coming out at about 480 °C, are used to provide the heat necessary to the reforming process first, and to superheat the methanol-water mixture afterwards. The heat amount necessary to heat and evaporate the liquid methanol-water mixture is provided by the hot glycol coming from the fuel cell at about 155 °C. The heat exchanger ensures the glycol releases all the remaining heat produced from the fuel cell in the heat exchanger and returns back in the electrochemical device at the inlet temperature of 145 °C. In this way the heat balance of the system is preserved and the operative temperature of the fuel cell is kept constant. A complete plant layout with all the components for the steady-state operative mode is given in Figure 2. It is important to note that both the evaporator and reformer are also equipped with an electrical heating supply, in order to ensure a proper safety heat supply, whatever the condition. In addition, the electric heat supply in the evaporator is of mandatory importance during the startup mode. In Figure 2, an overview of all the controls and measurement systems that should be present in the final layout is given.

3. Startup operations

When the system needs to be warmed up from environment temperature to the working temperature, the coolant loop is turned into a “warming loop” by transferring heat provided by burning methanol-water mixture to the circulating glycol (see Figure 1). Heat is transferred until the fuel cell reaches a temperature of about 120 °C. At this time, fuel and air are fed to the FC, which starts working and will be warmed up to 160 °C. The heating/cooling loop is reported in red in Figure 1: during the startup mode, the heating unit transfers heat to the glycol circuit and the heat exchanger fan is then off. During normal working operation, the electric heat supply is switched off and the heat exchanger fans will be on.

At the same time, heat is provided to the evaporator by electricity and it is used to evaporate a small amount of methanol-water mixture, which is mixed with external air and directly supplied to the catalytic burner. The combusted gases are employed to heat the reformer up to the operative temperature of 280 °C. In this phase, the glycol is not supplied to the evaporator. When the operative temperature is reached in all the components, the water-methanol gas mixture is fed to the reformer and the fuel cell starts working. Finally, in order to account for glycol volume expansion from environmental temperature to 160 °C, it is of paramount importance to insert an open expansion volume in the glycol circuit. A complete plant layout in startup mode is provided in Figure 3. The figure illustrates the presence of some three-way valves which have not been reported in Figures 2 for the sake of simplicity.

4. System description

Figure 4 shows the complete layout of the modelled reformer-fuel cell system: a liquid mixture of 40% CH_3OH and 60% H_2O (molar base) (1) is fed to an evaporator through a peristaltic pump. The mixture leaves this component in gas phase at about 250 °C (3) and is directed to the reforming unit in which more heat is provided and the reformate gas (4) leaves the reformer at 280 °C and then is directed to the fuel cell. The mass flow rate of reformate is relatively small compared with other flows involved in the system. Thereby, a cooling from 280 °C to 160 °C is considered to account for eventual heat losses from the reformer to the fuel cell (5). What is always mandatory, is to prevent any condensation of steam in the reformate mixture. A higher reformate gas temperature in the FC unit (within the life-compatibility of the fuel cell material) would only imply a slightly higher amount of heat to be removed from the fuel cell. The fuel cell operates at 160 °C and converts part of the inlet reformate gas with a fuel utilization factor (FU) of 80%. To do so, air is provided through a blower (25) at environmental temperature and off-air leaves the component at FC temperature (26). The off-fuel (6) is mixed with air provided by another blower (21) and fed to a catalytic burner. The combusted gas flow (22) leaves the burner at about 480 °C and is directed to the reformer, providing the necessary heat to convert the methanol-water mixture in a hydrogen rich gas. The glycol is made circulate by the pump (not represented in Figure 4) (31) and removes the heat generated in the fuel cell (32); the coolant mass flow rate flowing in the loop is calculated to ensure a maximum increment in glycol temperature across the fuel cell $\Delta T_{g,FC}$ = 10. Afterwards, the glycol crosses the evaporator, providing the necessary heat to evaporate the methanol-water mixture up to 140 °C (2). The evaporator, which in the final version of the system, is not electrical and will be heated by the glycol coming from the FC. Since the maximum operatin temperature for glycol is 155 °C, the methanol/water mixture cannot reach 250 °C. However, after the reformer, the comusted gas are hot enough to increase the temperature of the mixture up to 250 °C. Therefore in practice, the actual electric evaporator would be converted into a “two-stage” evaporator where in the first part, the mixture is evaporated by the glycol and in the second part the mixture is heated by the residual heat of combusted gas coming from the reformer. Further, the residual heat is released by the glycol in the heat exchanger (33). When the glycol leaves the heat exchanger, its temperature is the same as at FC inlet (145 °C). The combusted gas leaves the reformer at about 290 °C (24) and transfers more heat to the methanol-water vapor mixture increasing its temperature up to 250 °C. Afterwards, it is finally released in the environment (24).

As reported in Section 1, the fuel cells features 120 cells with an overall voltage of 72 V and a cell working point at 0,6 V and 0,4 A/cm^2. The stoichiometry is 1.5 for hydrogen and 2.5 for oxygen. A pressure drop of 0,2 bar was experimentally measured on the air side (cathode). As for the anode side, most of the pressure fall is due to the conversion of hydrogen into hydrogen ions. In this model, it is assumed that total the pressure drop is concentrated in the fuel cell, while all the other pressure falls are neglected for the sake of simplicity. The pressure drop should be measured experimentally and the final design of some components is not yet entirely defined. The aforementioned assumption does not significantly affect the obtained results. The measured pressure drop in the glycol loop is about 0,15 bar, but it depends on glycol viscosity, which consistently varies with temperature.

5. Conclusions

A hybrid system operating on methanol and using a battery pack together with a fuel cell stack was proposed and the plant layout was created. At this stage of the project the components will be assembled and established on the mobile transport (Fiat Skudo) to demonstrate the feasibility of the concept and optimize the operating conditions.

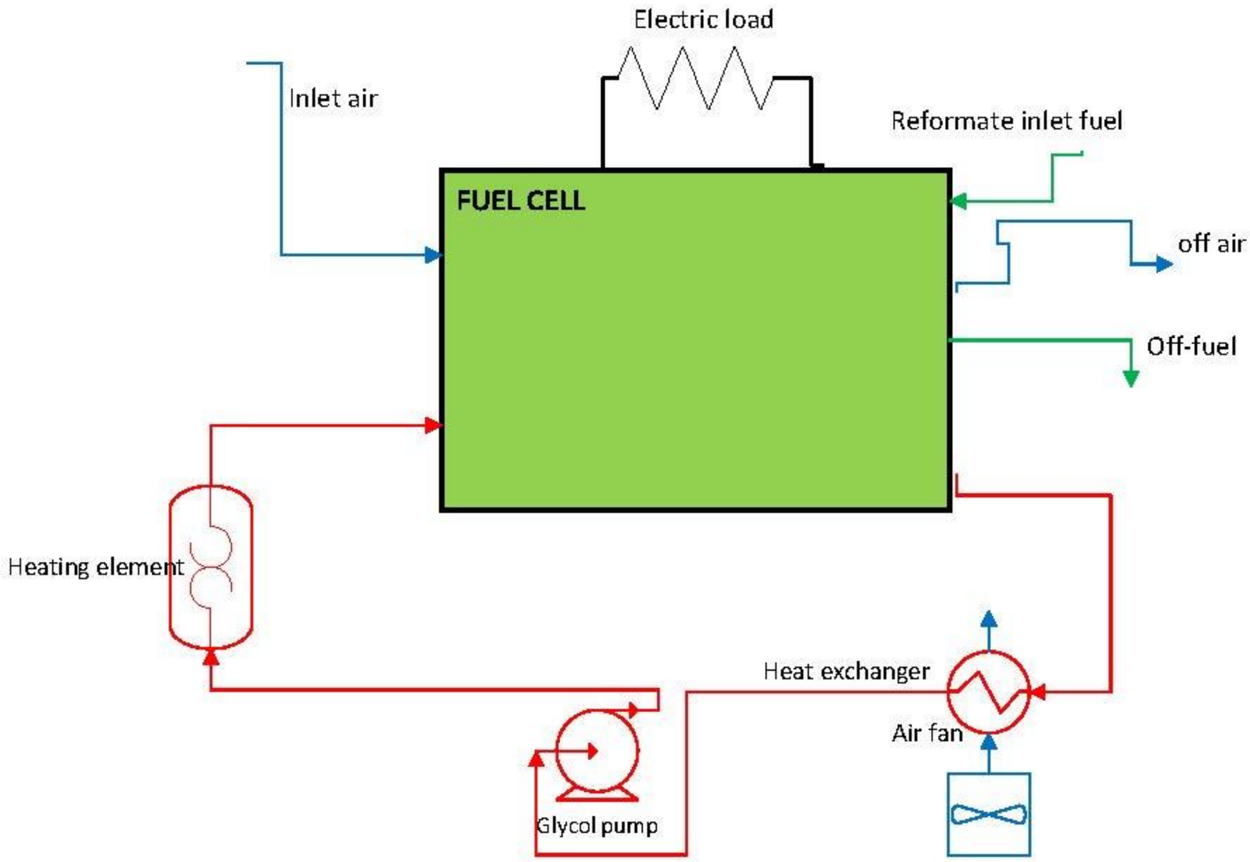

Figure 1. Conceptual layout of the hybrid system.

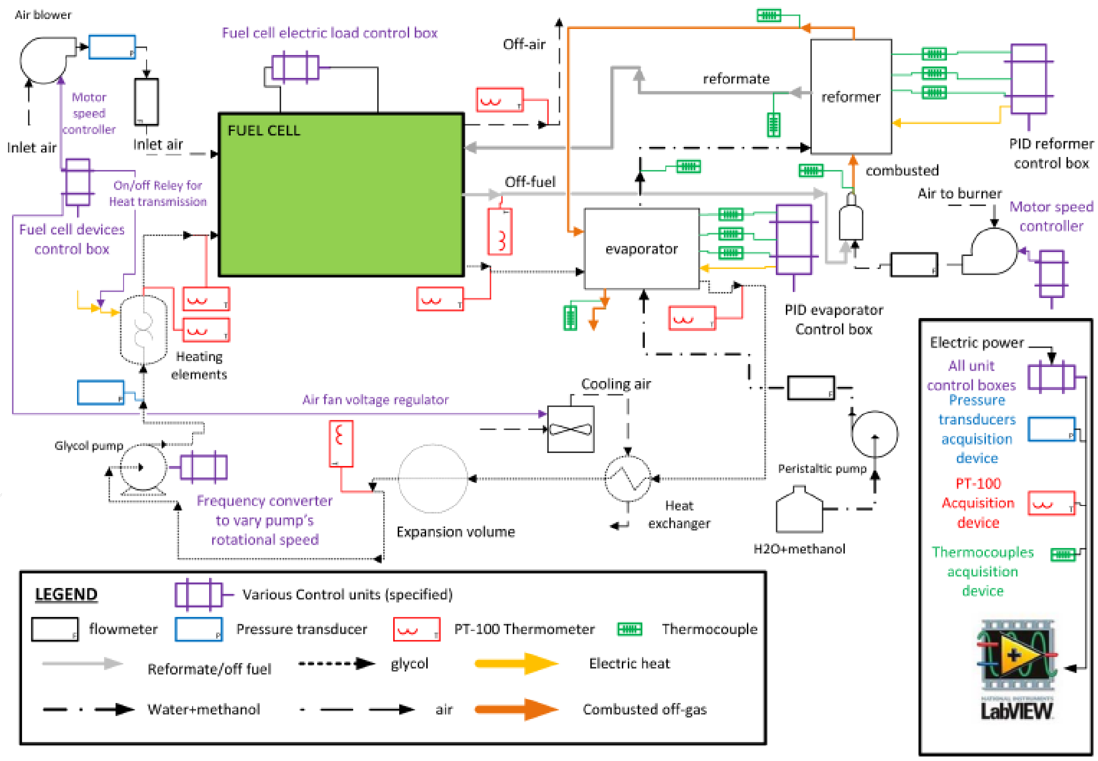

Figure 2. Complete methanol plant layout with measurement devices and control units.

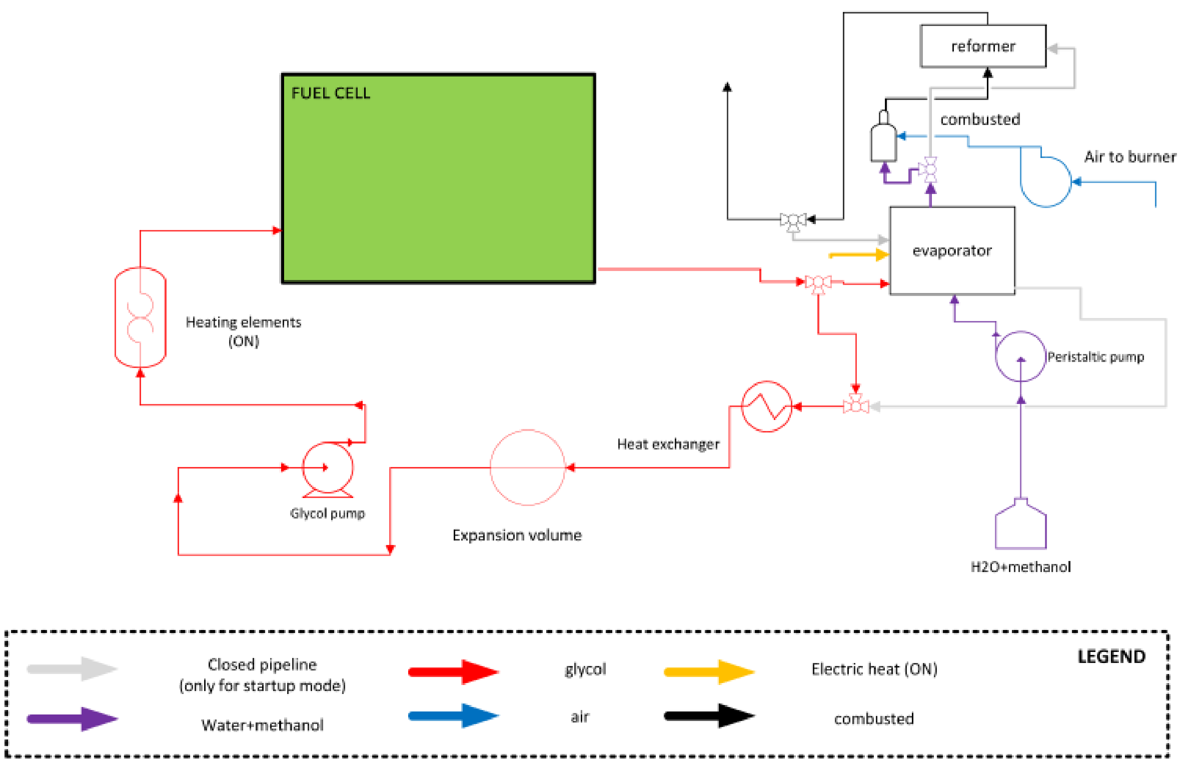

Figure 3. Methanol plant layout in startup mode.

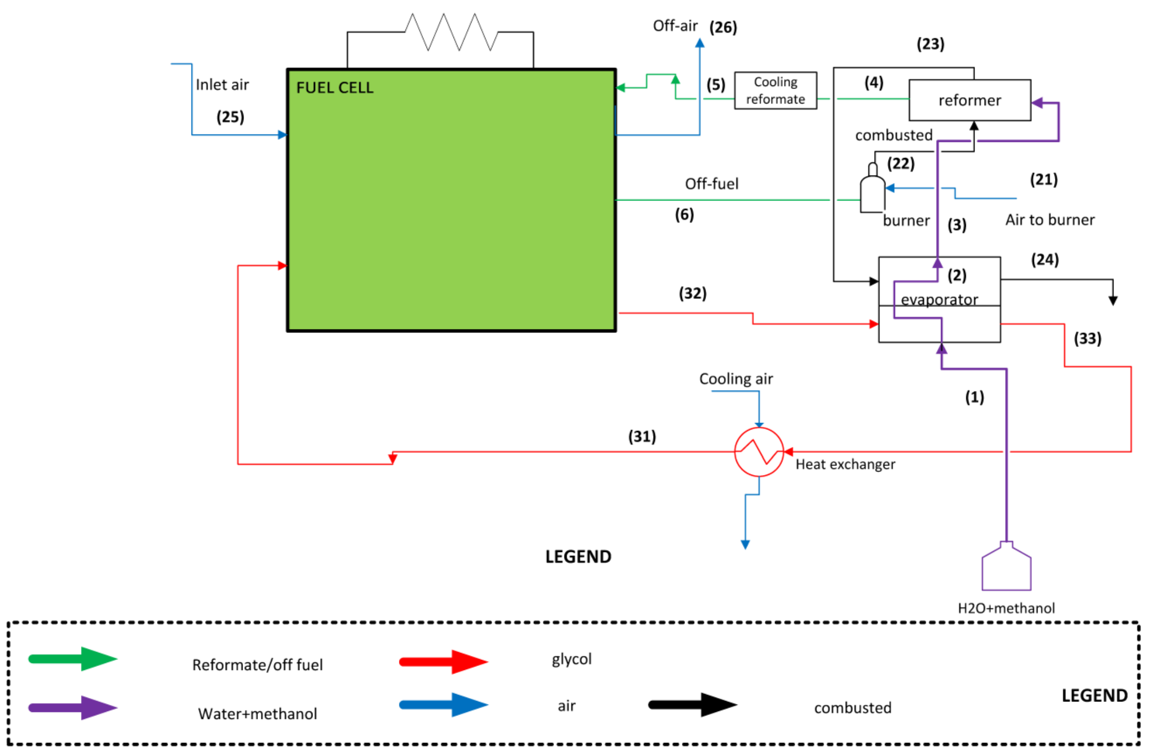

Figure 4. Layout of the modeled methanol plant.

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